U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

AD-A032 288

Satellite Trends and Defense Communications

Defense Communications Engineering Center Reston Va

Jun 76

329132

DDC

TN 20-76

DEFENSE COMMUNICATIONS ENGINEERING CENTER

AD A032288

TECHNICAL NOTE NO. 20-76

SATELLITE TRENDS AND DEFENSE COMMUNICATIONS

JUNE 1976

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

UNCLASSIFIED R740 28 May 1976

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TN 20-76	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Satellite Trends and Defense Communications		5. TYPE OF REPORT & PERIOD COVERED Technical Note
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) N. Abramson		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Defense Communications Engineering Center Advanced Systems Concepts Branch, R740 1860 Wiehle Ave., Reston, Va. 22090		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS n/a
11. CONTROLLING OFFICE NAME AND ADDRESS same as 9.		12. REPORT DATE June 1976
		13. NUMBER OF PAGES 27
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) n/a		15. SECURITY CLASS (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE n/a

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

n/a

18. SUPPLEMENTARY NOTES

Review relevance 5 years from submission date.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Defense Satellite Communications
Satellite Packet Broadcasting
Packet Broadcasting Networks
Economics of Satellite Networks

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report examines some of the long term trends in the economics of satellite communications networks and how these trends are reflected in the architecture of these networks. These trends are examined using data obtained from the INTELSAT series of commercial communications satellites and their effects on military satellite networks are also indicated.

TECHNICAL NOTE NO. 20-76

SATELLITE TRENDS AND DEFENSE COMMUNICATIONS

JUNE 1976

Prepared by:

- N. Abramson

Approved for Publication:

GEORGE E. WIEN, Acting Chief
Systems Engineering Division

FOREWORD

The Defense Communications Engineering Center (DCEC) Technical Notes (TN's) are published to inform interested members of the defense community regarding technical activities of the Center, completed and in progress. They are intended to stimulate thinking and encourage information exchange; but they do not represent an approved position or policy of DCEC, and should not be used as authoritative guidance for related planning and/or further action.

Comments or technical inquiries concerning this document are welcome, and should be directed to:

Director
Defense Communications Engineering Center
1860 Wiehle Avenue
Reston, Virginia 22090

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

This report examines some of the long term trends in the economics of satellite communications networks and how these trends are reflected in the architecture of these networks. These trends are examined using data obtained from the INTELSAT series of commercial communications satellites, since this data provides the clearest indication of satellite cost trends. The effect of satellite system developments on the special requirements of military satellite networks, is also indicated.

Even a casual observer of the communications satellite scene must be aware of the decrease in cost of satellite communications since the first commercial satellite system was placed in orbit in April 1965. The data herein quantifies this general impression and indicates what might be expected in the future. But before providing this data, it is emphasized that it would be a mistake to conclude from the data merely that the cost of satellite earth stations will decrease, that the number of such stations will greatly increase, and that the total cost of satellite communications will decrease. All of these things are likely but the mistake would be to infer from these changes that satellite communications networks of the future will be more numerous and lower cost reflections of the networks of today. The main point of this report is that the expected continuation of economic trends of the past 10 years offers opportunities for new forms of satellite system architectures, providing both lower cost and more flexible communications than exists today. Specifically, this report proposes the consideration of a system architecture that utilizes satellites in a "broadcast," as opposed to a point-to-point, mode. Clearly, before this or any other approach is selected, a broad analysis and cost tradeoff study will be needed encompassing the consideration of many factors beyond the scope of this paper; for example:

a. further definitization of future costs for satellites, earth terminals, etc., related to technology advances and/or economy of scale factors,

b. recognition of corresponding cost projections for terrestrial communications,

c. consideration of a host of additional issues and problems such as frequency and orbit position assignments, system vulnerability and reliability, and the development of suitable control and access techniques

For these reasons, the scope of this paper must be considered as being somewhat limited. However, it does represent one step towards the ultimate collection and evaluation of all the issues.

At the present time, satellite links are used almost exclusively as replacements for conventional point-to-point ground links in communications networks. In a network composed of point-to-point links connecting a large number of nodes, or message centers, it is not economic to connect every node to every other node. Therefore, it is usually necessary to route messages through a sequence of nodes, or switching centers, to transmit information between two nodes. This requirement for routing messages between nodes and for establishing large and often costly switching centers is a direct consequence of the use of point-to-point channels. Furthermore, the use of point-to-point channels in a military situation has certain significant disadvantages related to their inherent inflexibility and the requirement that each node rely on the integrity of adjacent nodes for the reception of its messages.

The natural structure of satellite communications links does not require the establishment of point-to-point communications channels in the traditional sense. A more natural form for satellite communications resources is a broadcast structure, allowing each network node to communicate directly with every other network node. The communications architecture which best matches the broadcast structure of the satellite communications channel is therefore one which starts from the premise that communications can proceed from many transmitters to many receivers in a communications environment analogous to that of a multi-person conference. Two immediate consequences of such an observation are that broadcast satellites provide convenient structures for teleconferencing and for mobile communications.

Since this report is concerned with the broadcast capabilities of communications satellites, it does not deal with satellite switching. For in a broadcast network, switching centers in orbit are as unnecessary as switching centers on the earth. It is noted, however, that it may be possible to design more advanced systems which use both onboard switching and broadcasting for special purposes, e.g., frequency re-use.

II. TRENDS

1. SATELLITE PARAMETERS

Table I gives some physical characteristics of the INTELSAT series of satellites and illustrates the rate of progress in the development of such systems. These satellites changes show the pace of communications satellite development during the past decade. The increase in the satellite effective

Table I. Physical Characteristics of Intelsat Satellites [1]

INTELSAT	Primary Usage Years	Diameter (cm)	Height (cm)	Weight (kg)	Band-width (MHz)	DC Power (watts)	Effective Radiated Power (watts)	Number of Telephone Circuits
I	1965-67	72	60	39	50	33	20	240
II	1967-68	143	68	86	130	75	35	240
III	1968-71	143	105	151	225	125	300	1200
IV	1971-78	240	532	721	432	500	2400	6000

radiated power is particularly significant in terms of its effect on satellite earth stations. Since INTELSAT I, almost all of the more than 110 earth stations used in the INTELSAT system have included a 30-meter diameter antenna, sophisticated tracking and control equipment to point this large antenna, and extremely sensitive cooled receivers to detect the weak signal from the satellite. While such ambitious earth stations may have been desirable for use with INTELSAT's I, II, and III, they seem overdesigned for use with INTELSAT IV, with an effective radiated power 120 times that of INTELSAT I.

Perhaps because the satellites are figuratively the most visible part of a satellite communications system, the cost of the satellites are often though to be the dominant cost in the total system. In fact, the total cost of satellite communications is composed of three separate components -- and in the present generation of satellites the cost of the satellite itself is rapidly becoming the smallest of these components. The three components of the total cost are the satellite cost, the earth station cost (including multiplexing equipment), and the cost of distribution from the earth station to the user.

2. SATELLITE COSTS

Cost estimates for the space segment of a single full duplex voice channel in the INTELSAT series of satellites have been provided by Roberts [2] and are shown in Table II. Comparable costs for the Anik and the Westar satellites are about $300 per voice circuit per year.

Table II. INTELSAT Cost Estimates [2]

INTELSAT	Primary Usage Year	Number of Voice Circuits	Lifetime (years)	Total Cost (Million $)	Cost Per Voice Circuit Per Year ($)
I	1965-67	240	1.5	8.2	22,800
II	1967-68	240	3	8.1	11,300
III	1968-71	1200	5	10.5	1,800
IV	1971-78	6000	7	26.0	600

The voice circuits referred to in Tables I and II are digital voice circuits with a bit rate of 56 kb/s. If the use of digital voice compression equipment is taken into account (reducing the data rate of a voice signal to 16 kb/s or even 2.4 kb/s), the number of available channels increases by a factor of from 3 to 20 and the cost per voice channel decreases correspondingly.

3. EARTH STATION COSTS

The cost of an earth station for a satellite communications system is more difficult to determine than the cost of the satellite. In analyzing the cost of an earth station it is necessary to specify the communications capabilities desired of the station. For example, almost all the first stations built for the INTELSAT system were capable of transmitting and receiving color television signals while simultaneously handling voice and data traffic. Furthermore, they were designed to have this capability with satellites transmitting considerably less power than the current generation of satellites. These earth stations typically consist of a 30-meter antenna, cryogenically cooled receivers, and tracking capabilities of questionable utility. The costs of such an installation have been in the range of $3,000,000 to $5,000,000. The costs for smaller and simpler earth stations used in the Canadian and U.S. domestic systems have been from $1,000,000 to $2,000,000 for full television and voice-data capabilities. If we consider earth stations with only data communications capabilities, then even simpler, less costly installations are possible [3]. Earth stations have been installed by U.S. domestic satellite carriers for specialized military data applications at megabit data rates ranging in cost from $100,000 to $400,000 per station, and future stations at even lower costs are projected.

Some of the factors that contribute to the lower cost earth stations include smaller diameter antennas, uncooled low noise receivers, low power transmitters, and simplified communications hardware requirements. In many instances, forward-acting error correction techniques can be added to the system at little additional cost to provide significant improvement in performance [4,5].

Another factor which significantly impacts earth station costs is equipment redundancy. Redundancy implies that additional components are provided for backup in the event of failure of online components. User reliability requirements will determine the need for redundancy. For example, assuming unmanned earth station operation, the expected reliability of a nonredundant earth station is 99.4% versus 99.9% for a redundant system. However, the cost of adding redundant components can amount to a significant portion of the total earth station cost; as much as 40% of the total cost of a simple single data link earth station. Thus, for a given expenditure level, a higher level of overall network reliability may be achieved by designing a network with a larger number of nonredundant earth stations. This subject is discussed further in Section III. 5, dealing with network survivability.

4. GROUND DISTRIBUTION COSTS

Common user earth stations can require extensive ground distribution circuits to connect with the user. This is particularly undesirable to the data user since it can add signficantly to the overall service cost and degrade the overall quality of service. For many small data terminal users, however, it is possible to collocate the earth station at the user's premises, thus reducing the ground interconnect costs to zero and ensuring a high grade of end-to-end performance. American Satellite Corporation has recently installed a "dedicated user" data network for DoD where all earth stations are collocated at the user's premises and the overall bit error probablity is nominally less than 10^{-8} for 1.344 Mb/s data service [6].

III. SYSTEM ARCHITECTURE

1. TRANSITIONAL PHASE

The short range consequences of the trends outlined in the previous section are fairly obvious. As the cost of satellite communications systems decrease, these systems will be used more and more extensively, first, in situations where no ground alternative is feasible (e.g., emergency communications in areas without ground facilities), and then in situations where ground alternatives are expensive (e.g., long distance, high traffic rate routes). As satellite communications links are first introduced into a network, they can be viewed simply as replacements for conventional point-to-point ground links. With the introduction of additional satellite links, however, the question of network connectivity starts to assume an importance unique to information networks with satellite links.

2. THE CONNECTIVITY PROBLEM

Consider the transmission of information in a network from A to B to C as shown in Figure 1a. If the ground links of the network are simply replaced by satellite links, as indicated in Figure 1b, then transmissions from A to C traverse a two-hop satellite path. Since each round trip satellite hop introduces a quarter second delay, the two-hop delay results in a half second time delay for a one-way trip from A to C. Such a delay will be perceptible for speech signals and will degrade the responsiveness of interactive information networks using multiple-hop satellite links. Of course, as the number of satellite hops increases beyond two, the problem of satellite delay becomes more serious. It should be pointed out, however, that a message switching data network employing multiple satellite hops might function successfully even in the presence of several seconds of satellite delay.

Another aspect of information networks formed by replacing ground links with satellite links may be illustrated with Figure 1. If a single satellite is used to transmit signals from A to C by means of a two-hop path involving B, the transmission from A to C through B requires twice as much satellite channel capacity as direct transmission from A to C. Again, as in the case of delay, this problem become more serious as the number of satellite hops increases.

If there are n earth stations which connect to a given satellite, the minimum number of point-to-point channels required so that every station is in one-hop contact with every other station (complete connectivity) is

$$\frac{(n)\,(n-1)}{2}.$$

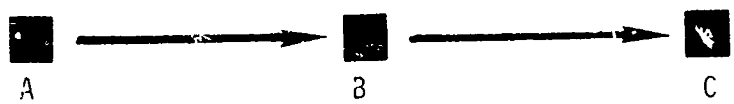

Figure 1a. Ground Network

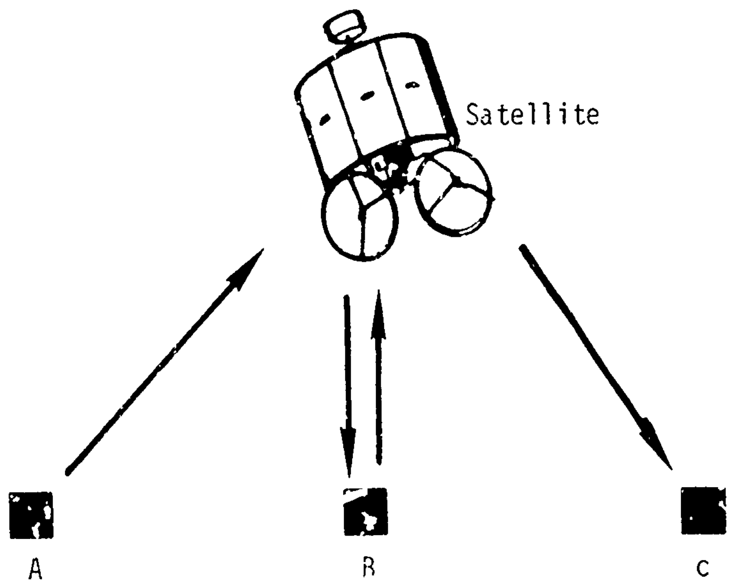

Figure 1b. Satellite Network

For example, the approximately 60 earth stations in the INTELSAT system which use the Atlantic satellite would require about 1800 point-to-point channels for complete connectivity. This would provide for only a single channel between each pair of stations.

In contrast to a ground based information network then, the problem of connectivity in a satellite network should not be solved by providing a sequence of switching nodes and routing messages through a large network by a sequence of hops from one node to the next. But this criterion for the use of satellite links has a potential benefit which makes the solution of the satellite connectivity problem an attractive objective for the network designer. If an architectural structure for the satellite network can be designed which achieves complete connectivity of earth stations, then the necessity for large switches to route traffic from node to node will have been eliminated.

3. BROADCAST CHANNELS

In order to understand how to solve the connectivity problem in satellites it is helpful to examine the differences between the satellite communications medium and the ground based channel. A satellite communications channel has a broadcast nature which allows it to receive and to transmit information from and to any earth station in its radiated pattern. Thus the connectivity desired in a satellite-linked information network already exists because of the nature of the satellite channel itself. A system architecture which forces the broadcast satellite channel to conform to the mold of point-to-point ground channels will lead to the appearance of a connectivity problem which should not exist.

The fact that a satellite channel is theoretically capable of providing a completely connected network does not guarantee that this kind of connectivity will be achieved in practice. But the practice of viewing the satellite channel in conventional ground terms will guarantee that such connectivity is impractical for large networks. What is needed, then, is a satellite system architecture which views the satellite channel as a satellite channel -- i.e., an architecture which does not unnecessarily impose point-to-point restrictions on a broadcast medium. One such system architecture is explained in Section IV.

4. SYSTEM TRADEOFFS

The improvements noted in satellite radiated power in the INTELSAT series of satellites allows the use of less costly earth stations. For example, there is about a 10 dB improvement in E.I.R.P. between the INTELSAT IV global beam and the spot beam of INTELSAT I; and another 10 dB between the spot beam of INTELSAT IV and the global beam of INTELSAT IV. Thus, all other factors being equal, the 30-meter dish used with INTELSAT I would be equivalent in performance to a 3-meter dish used with the spot beam of INTELSAT IV. In practice, however, the cost of the earth station is decreased by a number of factors, not just by decreasing the earth station antenna diameter.

The continuing decrease in earth station cost leads to a steady decrease in the distance at which the cost of a satellite channel equals the cost of a ground channel. But as this crossover distance becomes shorter and shorter, another cost factor enters which encourages the use of even larger numbers of small earth stations. A considerable fraction of the overall cost of a satellite or land based information network is accounted for by the land distribution costs -- the costs associated with connecting a user to a network port at a switching node or satellite earth station. As the nodes or earth stations become more numerous, the average distance from a user to a network port decreases, encouraging the use of even more small nodes in the network [6]. For ground networks, this factor is counterbalanced by the switching and routing complexities inevitable in a partially connected network with a large number of nodes. In fact, for ground networks, as the number of nodes is increased, the switching becomes more complex and the traffic handled by each node decreases, not by the reciprocal of the number of nodes but only as the reciprocal of the square root of the number of nodes, since each node must handle traffic destined for other nodes as well as its own traffic. For satellite networks operated in a broadcast mode, on the other hand, the network is completely connected. Routing from one earth station to another is never required and, as the number of earth stations is increased, the traffic handled by each node decreases as the reciprocal of the number of nodes.

5. SYSTEM RELIABILITY

As for ground distribution costs, there are large qualitative differences between the reliability factors in ground networks and satellite networks. The fact that a transmission path in a ground data network ordinarily passes through several switching points leads to higher values of bit error probability for such networks. Therefore, the number of nodes in a ground network increases, the error probability may also increase. For satellite data networks, however, the introduction of additional earth stations will ordinarily have no effect on the error probability of other earth stations in the network.

If a node in a ground data network goes out of service, the effect on the total capacity of the network need not be great if there is sufficient connectivity within the network. A certain amount of rerouting of data traffic destined for other nodes is required, but this is ordinarily not a major problem. For satellite data networks, the elimination of a single node need only affect the traffic meant for that node, and if each ground of user is clustered about a single node, collocation of the users with their earth station means that the communications is as survivable as the users. If users are not clustered about a single earth station in a network of small earth stations, it may be desirable to provide multiple connectivity for reliability as is ordinarily done for partially connected point-to-point ground links today.

Satellite data networks with a small number of large earth stations are subject to a number of vulnerability limitations common to any network where a large amount of traffic is concentrated at a small number of nodes. Thus a satellite network with, say, five earth stations used as concentration points for long haul communications is obviously vulnerable to hostile action at those five points. Approximately the same vulnerability would be exhibited by a CONUS ground network with five cross continent high capacity lines linking node concentration areas on the east and west coasts. But the earth stations are each vulnerable at a single point, while the cross continent point-to-point terrestrial lines could each be cut by hostile action taken at any point on the lines. The use of a large number of moderately sized earth stations can eliminate the concentration of a large amount of the data to only a few points in a network.

Perhaps the most striking case of a difference in the reliability characteristics between a cable network and a satellite network for military applications occurs in international networks. Because international point-to-point terrestrial channels must enter a country at fixed locations (usually a small number of such locations) and because international traffic using point-to- point channels is often routed through third countries, such traffic is subject to interruption because of changing political factors. In addition, even when such traffic is not interrupted, the fact that facilities controlled by a third country are required places the user at a political disadvantage. Satellite networks do not exhibit such properties. Since the satellite network is completely connected, routing through a third country can be eliminated and the network may be easily reconfigured to account for changing political as well as military requirements.

In addition to questions of vulnerability, there are basic reliability questions dealing with the comparison of ground networks and satellite networks with large numbers of earth stations. The basic point is made quite clearly in [7]: "In satellite communications, a single hop connection which involves two links in cascade can serve earth stations separated by great circle distances up to 17,000 km. A double hop connection with four cascaded links and two satellites is required for greater distances. These small numbers of links, compared to the hundreds required in land-based, line-of-sight communications systems, lead to high operational reliability provided that adquate care is given to the elements of the system."

Perhaps the most telling point dealing with the relative reliability of satellite channels and submarine cable channels is the fact that in 1974, "temporary service via satellite for submarine cable restoration comprised 24,920 half-circuit days" [7].

One of the methods by which earth station reliability has been maintained at levels of .9986 and above [7] is the use of redundant systems in earth stations. For the situation where there are only a small number of earth stations, or for earth stations which handle a significant fraction of the total system traffic, such redundancy makes sense. However, as pointed out in the discussion of earth station cost, the use of redundancy at earth stations can amount to as much as 40% of the total equipment cost of the stations. Thus, in satellite information networks with large numbers of earth stations, it is often desirable to increase overall system reliability by using a larger number of nonredundant earth stations. It should also be pointed out that the general survivability of the system in the face of hostile action is increased by employing additional stations.

The above discussion on survivability and reliability has centered on the earth station rather than on the satellite. This is because our primary concern here is the question of the number of such stations to use in a satellite information network. The vulnerability and reliability of the satellite then is not a factor in our attempt to analyze this question. Nevertheless, we should point out that satellite redundancy, alternative communications media, and perhaps satellite protection must be considered in any military satellite communications network.

IV. A PACKET BROADCASTING ARCHITECTURE

1. NETWORK OPTIMIZATION

Section III dealt with the general characteristics of a data communications network using large numbers of small earth stations in a broadcast mode. This section describes a specific data communications architecture which uses the broadcast property of satellite channels to provide a completely connected information network. The form of communications architecture described is called packet broadcasting [8], and is but one of a number of possible choices [9, 10, 11, 12, 13, 14] for a satellite data network using large number of small earth stations in a broadcast mode. The point of this section, then is not that the packet broadcasting system treated here is optimum in any sense, but that at least one system can be designed which is suitable for operation among many small earth stations operating in a broadcast mode. This is important in light of the discussion of the connectivity problem in the previous section which showed the limitations of operating satellite channels as if they were point-to-point channels in systems with many earth stations.

It should also be noted that the particular packet broadcasting system described is subject to a number of modifications and embellishments [10, 11, 12]; and is capable of being combined with other techniques based on more traditional switching concepts [13] in order to provide a phased transition from existing systems.

In order to choose among the many system design possibilities for such a network, it is necessary to analyze the various systems in terms of the existing channel traffic statistics and to compute the key parameters of an information network. Such parameters, for example, as average throughput, peak capacity, average delay, and maximum delay are often used to choose among different systems and to optimize key system parameters once a general network architecture has been selected. An analysis including such parameters is certainly a desirable input to the network evaluation process. To the extent that it is sensitive to existing traffic statistics, however, the analysis should be treated with some caution.

There are two reasons for such caution. First, the successful operation of an information network should not depend too strongly on any given set of traffic statistics; this network property is analagous to a property of statistical procedures, called "robustness." Simply stated, a robust network will operate satisfactorily over a wide range of statistical traffic fluctuations in addition to the average traffic used in its design. Such operation is necessary, of course, because the channel traffic statistics do vary from day-to-day and year-to-year; the requirements of real networks do change with changing operational requirements; and crisis situations can arise where channel measurements statistics, taken during a noncrisis interval, are meaningless.

The second reason for caution in using existing channel traffic statistics to "optimize" an information network is that the nature of a network can and should influence the channel traffic statistics. In fact, the interaction of network design and network traffic measurement can be viewed as an iterative process, where the nature of the network affects the kind of usage in the network, and the kind of operational usage observed in the network affects the network design. In other words, network traffic statistics measure only the situation here and now and not the desired situation, except for the case of a network which fully satisfies all its users in terms of the quality and cost of service.

2. PACKET BROADCASTING

Packet broadcasting information networks come in a variety of forms. Since the key departure of such networks is the broadcasting feature employed for data communications, most of these networks employ radio channels, although one organization has considered the use of packet broadcasting techniques on a cable television channel [14]. Most packet broadcasting networks and packet broadcasting experiments to date have involved ground-based systems. These include the ALOHANET at the University of Hawaii [15], the ARPA packet radio experiment [16, 17, 18, 19, 20, 21]; an experimental system now under construction at the Korean Institute of Science and Technology, Seoul; and a demonstration system for developing countries at the UNDP International Computer Education Centre, Budapest.

The use of the packet broadcasting technique on a satellite channel was demonstrated for the first time in 1973 in a NASA experiment involving the ALOHA system at the University of Hawaii, the University of Alaska, and the NASA Ames Research Center in California. A two-year satellite packet broadcasting experiment using large INTELSAT earth stations and the Atlantic Ocean INTELSAT IV satellite began in September 1975 [25].

Various satellite packet broadcasting techniques all employ variants of what is now called an ALOHA channel. Consider a number of earth stations, each wanting to transmit data packets over the same high speed communications channel. Assume that the rate at which the stations generate packets is such that the average time between packets from a single station is much greater than the time needed to transmit a single packet.

Conventional time or frequency multiplexing methods, or some kind of polling scheme, could be employed to share the single channel among the users. Some of the disadvantages of these method are discussed by Carleial and Hellman [22] and by Roberts [11]. The method used in an ALOHA channel is suggested by the statistical characteristics of the packets generated at the earth stations. Since each station will generate packets infrequently, and each packet can be transmitted in a time interval much less than the average time between packets, the following scheme seems natural.

Each station transmits its packets over the single high speed satellite channel in a completely unsynchronized (from one earth station to another) manner. Each packet contains a destination address in its header, so that each earth station can monitor the downlink satellite channel and select those packets meant for that earth station. As long as the average data traffic in the channel is low, the probability that two packets will overlap and that data will be lost, is low. If an overlap does occur, however, the statons which originated the overlapping packets will detect the overlap and can repeat the packets until they are received without error.

A representative of this transmission method is shown in Figure 2. This type of operation was first described in [23] where it was proven that the maximum data rate of such a channel was about 18% of the maximum rate attainable by a continuous data stream in the channel. Subsequently, a number of modifications of this method were described which allowed operation at from 36% to 90% of the data rate of a continuously transmitting channel [3, 10, 11, 12].

The percentages quoted above were all calculated with the model of a channel operating under a peak power limitation. For a communications satellite, however, the fundamental limitation on channel capacity is an average power limitation. Packet broadcasting systems offer significant advantages from the point of view of efficient utilization of average satellite power since the satellite transponder need only be provided power during the short bursts when it is transmitting a packet. Thus, a satellite transponder operating in a packet broadcasting mode at a duty cycle of 10% would only transmit 10% of its rated power. Alternatively, such a transponder could be adjusted to provide 10 dB more power during its packet transmissions, while keeping its average power output fixed. Recent results [24] have shown that this mode of operation allows packet broadcasting systems to operate at close to the maximum possible channel data rate for a given satellite bandwidth and a given average power.

3. PACKET BROADCASTING SYSTEM CONSIDERATIONS

The preceding section mentioned that various methods of a packet broadcasting provided system data rates ranging upward from 18% of the continuous channel rate to close to 90% of the continuous channel rate. Of course, the throughput of an information network is not the only criterion used to design a network; questions involving cost, flexibility, delay, reliability, and operating conditions must all be considered For military networks, questions of vulnerability and susceptibility to jamming and spoofing are also important. This section summarizes the major considerations involved in determining the throughput of a packet broadcasting network and discusses how these considerations affect the other factors mentioned.

An examination of some of the references already mentioned [10, 11, 12] will provide examples of different systems, each of which seems to have clear advantages over all others the authors have considered. In fact, each system

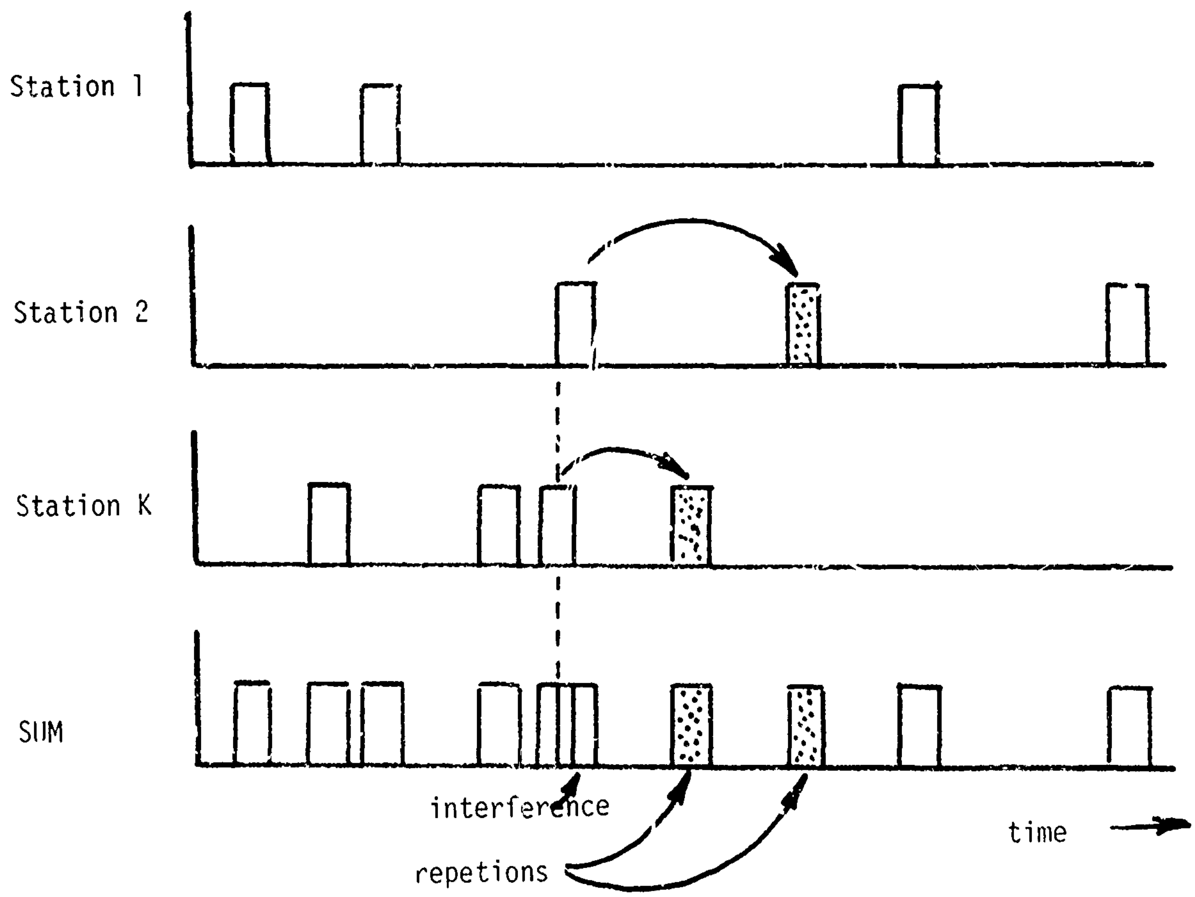

Figure 2. The ALOHA Channel

does have a clear advantage if one is careful in selecting the kind of traffic used to compare the various systems. The primary reason for the lack of a definitive selection in the search for a "best" system is uncertainty in the definition of the traffic that the system must handle. A complete analysis of this issue would be impractical in this report, but a few examples will serve to explain the reason for so many contradictory conclusions by so many authors.

The simple ALOHA packet broadcasting procedure described in Section IV.2, provides a maximum throughput of 18%, under the assumption that there are a large number of earth stations, each transmitting packets of the same length. If the packets are of different length, it can be shown that the maximum channel throughput is less than 18%. If, however, the channel is modified slightly, and uses what is called a slotted ALOHA channel [3], the maximum value of the throughput becomes 36%. For a slotted ALOHA channel, if a finite number of stations are assumed, the maximum throughput is greater than 36%, and if one station (or a small number of stations) transmits almost all of the packets, the maximum throughput will approach 100% [3].

These results have suggested to some that the slotted ALOHA channel has a large advantage over an unslotted channel in the maximum achievable throughput. And indeed, such a slotted channel is being used on an ARPA sponsored packet broadcasting experiment using the Atlantic Ocean INTELSAT IV satellite [25]. But a slotted channel presumes that all packets to be transmitted are of the same length. Measurements over the ARPANET and otherincomplete measurements over the ALOHANET suggest that packet lengths within a given network tend to vary greatly. Since the maximum possible advantage of a slotted channel is a factor of two in throughput, the variation of packet lengths by a factor of two or more can offset this advantage. But this discussion tends to over-simplify a complicated design choice. For, if the earth stations to be used in a packet broadcasting network are large, as are the stations in the ARPA Atlantic Ocean INTELSAT experiment, the multiplexing equipment at the earth station can be used to format uniform length packets and to regularize the data flow in other ways.

The regularization of data flow in a packet broadcasting network brings up the question of reservation schemes in such systems. As shown in [22], a packet broadcasting network has its greatest advantage over FDMA, TDMA, or polling methods when the peak to average data rate is high and when the net is composed of a large number of earth stations. Even under these conditions, however, network traffic may be a mix of interactive (data or voice) packets and file packets. File packets have the characteristic of arriving infrequently, but in large groups of 10^4 or more packets at once. If file packets are transmitted in the same manner as interactive packets, they may block the network (albeit at infrequent intervals), or they may experience unacceptably large delays [28]. A rather obvious way of accommodating such traffic is to use a standard packet to make a reservation for the file -- in effect preempting the channel for some fixed period known to all earth stations and transmitting the file during the preempted period. Several systems of this sort have been proposed [10, 11, 12, 26, 27] and again each of these schemes can be shown to function well under certain ranges of channel traffic statistics. It does not appear than any one of these reservation systems have any clear advantage over the others in terms of throughput and delay -- the usual criteria by which the systems are measured. For most practical networks, it probably does not make much difference which reservation scheme is chosen as long as throughput and delay are the only criteria used.

The choice of which method to use in the design of an information network should probably be made in terms of the other considerations mentioned at the beginning of this section. In spite of the confusing number of criteria mentioned as necessary for consideration in network design, there is one overriding design principle which can serve to clarify the situation: in the design of any kind of broadcast system, the simplicity in hardware, software, and operational characteristics of the broadcasting units should be the primary concern.

The simple packet broadcasting technique described in Section IV.2, observed this design principle. In situations where this technique can function effectively, the introduction of reservation systems to increase the theoretical throughput should be carefully justified. And the selection of various modifications to a basic packet broadcast mode should be made with considerable attention to the criterion of design simplicity, and the other criteria mentioned at the beginning of this section.

It seems clear that certain modifications to a basic system will be desirable for networks with a mix of interactive, message, file, and voice packets. The short term fluctuations which could be introduced into an unstructured packet broadcasting network by a long file would be unacceptable except for system operating well below capacity. When packet broadcasting networks are designed as additions to, or extensions of, existing networks, especially circuit-switched networks, certain kinds of structure are necessary to ensure smooth interfacing. But the overriding consideration in the choice of structure to impose on the packet broadcasting network should be simplicity and flexibility -- the consideration of maximum throughput will rarely loom as important in practice as it does in the literature of packet broadcasting theory.

A major factor in realizing the system simplicity inherent in most packet broadcasting systems is the modularity of the architecture for such systems. The operation of a packet broadcasting network is set up to accept a sequence of data bits, attach a header containing destination address, originating address, and perhaps other control information, and ship the packet out on a common data channel of some sort. This mode of operation has been compared to the operation of a mail system -- where the data bits correspond to a letter and the header corresponds to the envelope used to package the letter for transmission in the system. A mail system can accept letters and even packages of vastly different sizes and formats, route these items through the mail system in accordance with the address on the item, and operate successfully with a minimum of coordination among the users of the system. Different classes of mail can be established to meet the requirements of different classes of users and resource sharing among large number of users makes the system relatively insensitive to fluctuations of individual users.

The modular architecture of a packet broadcasting network provides an electronic analog to all these properties of a mail system. A packet broadcasting network can accept packets of different sizes and different formats. It is even possible to operate different subnetworks with incompatible modulation methods in the same band, and, if desired, to join these subnetworks in subsets of nodes which can recognize different modulation methods as desired. It is possible to structure the network to transmit files as discussed above, and even to include a certain amount of circuit-switched capacity in compatible operation with a packet broadcast architecture [13]. Different priority classes of packets can be established in a natural manner within the packet header and a satellite packet broadcasting network is structured to allow flexible re-allocation of system capacity in the face of individual traffic fluctuations.

The importance of this flexibility and system modularity is most evident in the establishment and in the phased growth of a packet broadcasting network and in the modification of existing networks. In contrast to some architecture configurations, packet broadcasting networks can be established with a relatively modest initial system. The operation of the network can be tested with a small number of nodes, and, perhaps more importantly, the system can be operated initially without the use of any reservation system or other refinement. As the system load builds up, it is possible to implement increasingly complex reservation systems in order to increase the overall network throughput. As such reservation systems are put into operation, they can be phased in by gradual stages over small subsets of networks users without disturbing the operation of the network for other users.

This kind of modularity and system development flexibility is in marked contrast to conventional line-switched systems using store-and-forward nodes and routing algorithms. In conventional networks, the introduction of a new node into an existing network requires coordination among all existing nodes in order to reconfigure the routing tables and coordinate new traffic patterns. In a packet broadcast network, however, the establishment of a new network node requires no network reconfiguration and no changes in routing algorithms. The ID for the new node is simply activated and the node is absorbed into the network without network modifications.

4. RELIABILITY, VULNERABILITY, AND JAMMING

Section III.5, discussed certain reliability questions relating to the use of satellites and small earth stations. This section is concerned with reliability, vulnerability, and jamming aspects of packet broadcasting architecture when used with these small earth stations.

The modularity of a packet broadcasting information network, as described in the previous section, has a number of desirable consequences when questions or reliability are brought up. The fact that nodes in such a network are independent in terms of routing provides the most obvious improvement over conventional networks using store-and-forward switching nodes. When one node is eliminated from the network, there is no need to re-route traffic and there is no decrease in the capacity of the network. The simplicity of the architecture in such systems is another feature which can lead to high reliability. The front end equipment necessary to provide multiplexing at a packet broadcasting earth station is similar to that of a TDMA system, without the requirement for coordination among the nodes in the network required by conventional TDMA. Since the address of each received pulse is examined and the pulse is discarded unless it has the correct ID, the multiplexing equipment can consist of a moderate speed minicomputer with a hardware ID verification unit of an input port.

The above reliability refers to the overall operational system and hardware reliability of a packet broadcasting network. In addition to this kind of reliability, the important consideration of data reliability - or error control - should also be mentioned. Operating experience over the past few years with existing satellite communications channels indicate that error probabilities as low as, or lower than, those of comparable ground based microwave channels can be expected [30]. Because of the modular character of packet broadcasting, however, it is possible to insert variable levels of error control to account for variable operating conditions. For example, in certain packet broadcasting experiments carried out over ATS-1 by the ALOHA system, auto ignition burst noise was found to cause measureable deterioration of data reliability under some low transponder power conditions in the satellite. In order to combat this problem, a variable level of error correcting coding has been designed to employ additional coding redundancy and thus additional correction capabilities, as needed. Since the coding and decoding is done locally at each terminal, the variable coding can be put into operation at only those nodes where it is necessary, while all other nodes continue to operate in a normal fashion.

Although the problem of error control in data networks has received considerable attention in the literature, in practice another problem can affect the usefulness of a network to as great, if not greater, degree. This is the problem of connection reliability - as opposed to data reliability -- the problem of opening and maintaining a connection between a sender and a receiver. It is hard to collect meaningful statistics on this problem, but most users of interactive information networks would agree that connection reliability sometimes limits the value of the network to the user. Connection reliability is enough of a problem on standard commercial circuit switched voice channels that all phone companies have clearly defined (and frequently used) procedures for reestablishing broken connections and adjusting charges on calls which experience broken connections. In a packet broadcasting network, the problem of connection reliability, in this sense, does not exist; since the broadcast channel eliminates the requirement for switching to establish connections between input and output, there are no fixed connections to be broken by switching malfunctions.

Finally, there are some simple observations which can be made concerning the vulnerability of packet broadcasting networks to jamming. The antijam protection of a conventional data link is ordinarily characterized in terms of the power advantage required by the jammer to eliminate the communications capability of the link. If we employ some form of bandwidth spreading by frequency or time hopping, or by a pulse address system, an additional penalty can be imposed on the jammer in terms of the power advantage he must have. Any of these conventional antijam techniques may be employed in a packet broadcasting system in the same manner as in circuit-switched systems or in packet-switched systems. Most of these techniques are required to be rather inflexible in that if the jammer can achieve the required power advantage, he can interfere with the effective functioning of the channel.

In addition to the techniques mentioned above, a packet broadcasting system can achieve an enhanced level of antijam protection simply by its burst nature. The basic design of a packet broadcasting system assumes the existence of jamming pulses from other users of the system. Thus, if a jammer wishes to jam a packet broadcasting channel continuously, he must employ a power advantage of at least e=2.718, even if the channel is used at capacity. Under more realistic assumptions of a packet broadcasting channel operated with a throughput of 0.10, the continuous jammer requires a power advantage of 10 dB. If the jammer operates in a pulse mode, the jammer will absorb some fraction of the channel throughput -- depending on how many pulses he can transmit.

Even more interesting is the possibility of using the burst nature of a packet broadcasting channel to combat jamming by decreasing its data rate and increasing its peak power while keeping its average power fixed. As an extreme case, if earth stations transmitters with modest average power output, but megawatt peak power output, could be used, a 10 MB/s satellite transponder might be employed to transmit data at only 10 b/s in a packet broadcasting burst mode. Such a 10 b/s channel would have a 50 dB antijam advantage; furthermore, such a channel could be of special value in a crisis situation since it would operate in a broadcast mode to allow transmission to many earth stations simultaneously.

V. CONCLUSIONS

Because of the limited scope of this report, as delineated in the Introduction, it is difficult to provide a proposed "solution" to future DoD communications with any high degree of certainty. However, two conclusions can be inferred with reasonable assurance, namely,

a. the role of satellites in DoD communications will likely increase from present levels, and

b. to more efficiently use satellite resources, other operating modes, such as the broadcast mode discussed in the paper, need to be investigated as alternatives to the presently common point-to-point mode.

REFERENCES

[1] Frederick J. Altman, et al, Satellite Communications Reference Data Handbook, Computer Sciences Corporation (July 1972).

[2] L.G. Roberts, "Data by the Packet," IEEE Spectrum, II, No. 2 (Feb 1974) pp 46-51.

[3] N. Abramson, "Packet Switching with Satellites," AFIPS Conference Proceedings, 1973 National Computer Conference, Vol. 42 (1973) pp 695-702.

[4] Eugene R. Cacciamani, Jr., "The SPADE Concepts Applied to a Network of Large and Small Earth Stations," Communication Satellite for the 70's; Technology, edited by N.E. Feldman & C.M. Kelly, MIT, Vol 25 (1971) pp 559-72.

[5] E.R. Cacciamani, Jr., "The SPADE System as Applied to Data Communications and Small Earth Station Operation," COMSAT Technical Review, 1, No. 1, (1971) pp 171-182.

[6] DCEC TN 15-75, "An Advanced Communications System Concept Employing Demand Assignment Satellites," R.D. Rosner, Mar 1975.

[7] B.I. Edelson, R. Strauss, and P.L. Bargellini, "INTELSAT System Reliability" Proceedings of the International Astronautical Federation XXVth Congress, Amsterdam (30 Sep - 5 Oct 1974).

[8] R.M. Metcalfe, "Packet Communication," MAC TR-114, Project MAC, Mass. Institute of Technology, Cambridge, Massachusetts, Dec 1973.

[9] J.G. Puente and A.M. Werth, "Demand Assignment Service for the INTELSAT Global Network," IEEE Spectrum, 8, No. 1 (Jan 1971) pp 56-69.

[10] R. Binder, "A Dynamic Packet Switching System for Satellite Broadcast Channels," Proc International Conference on Communications, San Francisco, June 16-18, 1975 (ICC 75).

[11] L.G. Roberts, "Dynamic Allocation of Satellite Capacity Through Packet Reservation," AFIPS Conference Proc, National Computer Conference, AFIPS, Vol 42 (Jun 1973) p 711.

[12] W. Crowther, et al, "A System for Broadcast Communications. Reservation ALOHA," Proc of the Sixth Hawaii International Conf on System Sciences, Western Periodicals, Inc., Jan 1973.

[13] DCEC TC 8-75, G.J. Coviello and P.A. Vena, "Concept for an Integrated Circuit- and Packet-Switched Telecommunications System," Jan 1975.

[14] I.T. Frisch, "Technical Problems in Nationwide Networking and Interconnection," IEEE Transactions on Communications, Jan 1975.

[15] N. Abramson and F. Kuo, Computer Communication Networks, Prentice-Hall, Inc. (1973) Chapter 14, "The ALOHA System."

[16] Robert E. Kahn, "The Organization of Computer Resources into a Packet Radio Network," AFIPS Conf Proc, Vol 44, 75 NCC, May 75, pp 177-186.

[17] R. Binder, et al, "ALOHA Packet Broadcasting - A Retrospect," AFIPS Conf Proc, Vol 44, 1975 National Computer Conf, May 1975, pp 203-216.

[18] S.C. Fralick and J.C. Farrett, "Technological Considerations for Packet Radio Networks," AFIPS Conf Proc, Vol 44 1975 National Computer Conf, pp 233-244.

[19] J. Burchfiel, et al, "Functions and Structure of a Packet Radio Station," AFIPS Conf Proc, Vol 44, 1975 National Computer Conf, May 1975, pp [illegible].

[20] H. Frank, et al, "Packet Radio System - Network Considerations," AFIPS Conf Proc, Vol 44, 1975 National Computer Conf, May 1975, pp 217-232.

[21] L. Kleinrock and F. Tobagi, "Random Access Techniques for Data Transmission over Packet Switched Radio Channels," AFIPS Conf Proc, Vol 44, 1975 National Computer Conf, May 1975, pp 187-202.

[22] A.B. Carleial and M.E. Hellman, "Bistable Behavior of ALOHA-Type Systems," IEEE Transactions on Communicatons, Apr 1975, pp 401-409.

[23] N. Abramson, "The ALOHA System - Another Alternative for Computer Communication," 1970 Fall Joint Computer Conf, AFIPS Conf Proc, Vol 37, pp 281-285.

[24] DCEC TN 38-75, "Satellite Packet Broadcasting To Very Small Earth Stations," N. Abramson, Sep 1975.

[25] R. Binder, et al, Bolt Beranek and Newman, Inc., "The Atlantic Satellite Packet Broadcast and Gateway Experiments," Apr 1975.

[26] N.T. Gaarder, "ARPANET Satellite System Note 3," The ALOHA SYSTEM, University of Hawaii, Honolulu, Apr 1972.

[27] H.R. Hwa, "A Conflict Free ALOHA System," Sydney/ ALOHA Working Paper #5, University of Sydney, Australia, Mar 1975.

[28] L. Kleinrock and S.S. Lam, "Packet Switching in a Multiaccess Broadcast Channel: Performance Evaluation," IEEE Trans on Communications, Apr 1975

[29] I. Gitman, "On the Capacity of Slotted ALOHA Networks and Some Design Problems," IEEE Trans on Communications, Mar 1975, pp 305-317.

[30] N. Abramson and E.R. Cacciamani, "Satellite Data Communications," IEEE Spectrum, to be published.